FORECASTING OF RAINFALL USING STATISTICAL DOWNSCALING MODEL (SDSM) – GENERAL CIRCULATION MODEL (GCM) FOR FUTURE ESTIMATION OF RAINWATER HARVESTING

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For my parents, who supported me with love and understanding. And also my sisters and my partner, whom has provided patience advice and guidance throughout the research process. Thank you all for your unwavering support.

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ABSTRACT

Changes in the spatial and temporal rainfall pattern affected by the climate change need to be investigated as its significant characteristics are often used for managing water resources. In this study, the impacts of climate change on rainfall variability in Johor was investigated by using General Circulation Model (GCM) on the availability of daily simulation for three representative concentration pathways (RCP) scenarios, RCP2.6, RCP4.5 and RCP8.5 for interval year of Δ2030, Δ2050 and Δ2080. In addition, the annual future rainfall trend and harvested rainwater volume estimation for the first interval year of Δ2030 were also made. Daily rainfall series from eight (8) stations in Johor capturing 30 years period (1988-2017) with less than 10% missing data were chosen. Of all 26 predictors, only five (5) were chosen for each station to form a rainfall equation at each station for prediction analyses. It can be observed that the temperature (nceptemp), surface specific humidity (ncepshum) and near-surface relative humidity (nceprhum) had a strongest influence in the local weather formations with R values ranged from 0.5 to 0.7. The annual mean rainfall for RCP 2.6, 4.5 and 8.5 was predicted increase by of 17.5%, 18.1% and 18.3%, respectively as compared to historical data. Kluang was predicted to receive the highest amount of rainfall, and the lowest was in Segamat. Moreover, the Mann-Kendall test was used to detect the trend and resulted in no trend for RCP 2.6. Even so, RCP 4.5 showed a significant upward trend in Muar and Kota Tinggi, and for RCP 8.5, all regions were detected to have an upwards trend except for Pontian and Kluang. Volume harvested rainwater (V_R) was calculated, which resulted in increment of 16.8% for both RCP 2.6 and RCP 4.5. However, RCP 8.5 gave the highest possibility to store harvested rainwater with 18.3% increment in the future. In general, the concentration of greenhouse gases from RCP 8.5 gave the highest rainfall in future. Thus, the results will be useful in evaluating the performances of the rainwater harvesting system in Johor incorporating climate change for future research.

ABSTRAK

Perubahan corak hujan dalam masa dan ruang yang dipengaruhi oleh perubahan iklim perlu diselidiki kerana ciri-ciri pentingnya sering digunakan untuk mengurus sumber air. Dalam kajian ini, kesan perubahan iklim terhadap kebolehubahan curahan hujan di Johor disiasat dengan menggunakan *General Circulation Model* (GCM) terhadap ketersediaan simulasi harian untuk tiga *Representative Concentration Pathways*, RCP2.6, RCP4.5 dan RCP8.5 tahun selangan Δ2030, Δ2050 dan Δ2080. Corak tahunan curahan hujan masa hadapan dan anggaran jumlah air hujan yang dituai untuk tahun selangan pertama Δ2030 juga dibuat. Data hujan harian dari lapan (8) stesen di Johor yang merangkumi tempoh 30 tahun (1988-2017) dengan kurang dari 10% data yang hilang telah dipilih. Dari semua 26 ramalan, hanya lima (5) yang dipilih untuk setiap stesen untuk membentuk persamaan hujan di setiap stesen untuk analisis ramalan. Kajian ini menunjukkan bahawa suhu (nceptemp), kelembapan spesifik permukaan (ncepshum) dan kelembapan relatif permukaan (nceprhum) mempunyai pengaruh paling kuat dalam pembentukan cuaca setempat dengan nilai R berkisar antara 0.5 hingga 0.7. Hujan purata tahunan untuk RCP 2.6, 4.5 dan 8.5 diramalkan meningkat masing-masing 17.5%, 18.1% dan 18.3% berbanding dengan data sejarah. Kluang dijangka akan menerima jumlah curah hujan tertinggi, manakala Segamat terendah. Seterusnya, ujian Mann-Kendall digunakan untuk mengesan corak hujan dan hasil daripada analisis, RCP 2.6 tidak menunjukan sebarang corak perubahan di masa hadapan. Walau bagaimanapun, RCP 4.5 menunjukkan corak kenaikan yang signifikan di Muar dan Kota Tinggi, dan untuk RCP 8.5, semua wilayah dikesan mengalami kecenderungan meningkat kecuali untuk Pontian dan Kluang. Isi padu takungan air hujan di hitung (V_R), akan mengalami kenaikan 16.8% untuk RCP 2.6 dan RCP 4.5. Walau bagaimanapun, RCP 8.5 berkemungkinan boleh menyimpan air hujan yang dituai dengan kenaikan 18.3% pada masa akan datang. Secara umum, kepekatan gas rumah hijau dari RCP 8.5 memberikan curahan hujan tertinggi pada masa depan. Oleh itu, hasilnya akan berguna dalam menilai prestasi sistem penuaian

air hujan di Johor yang menggabungkan perubahan iklim untuk penyelidikan masa hadapan.

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LIST OF SYMBOL AND ABBREVIATIONS

P_x	-	Estimates the missing value
SE	-	Standard error
ABS	-	Absolute
Z	-	The standard test statistic
V_R	-	Volume harvested rainwater
R	-	mean monthly rainfall
H_{RA}	-	consider 10 household roof area (100 m^2)
R_C	-	runoff coefficient (0.75)
(R)	-	coefficient of correlation
GCMs	-	General Circulation Models
SDSM	-	Statistical Downscaling Model
RCPs	-	Representative Concentration Pathways
RWH	-	Rainwater harvesting
DID	-	Department of Irrigation and Drainage
NCEP	-	National Centres of Environmental Prediction
CanESM2	-	Canadian Earth System Model 2
RCE	-	Radaitive-moist-convective equilibrium
EBMs	-	Energy Balanced Model (EBMs)
CanESM2	-	Canadian Earth System Model (CanESM2)
CTEM	-	Terrestrial Carbon Model
CMOC	-	Ocean Carbon Model
CCCma	-	The Canadian Centre For Climate Research Modelling and Analysis
WCRP	-	World Climate Research Program

IPCC	-	Intergovernmental Panel on Climate Change
RCM	-	Regional climate model
NEM	-	North-east monsoon
SWM	-	South-west monsoon
MK	-	Mann-Kendall test
WMO	-	World Meteorologist Organization
SR	-	Spearman’s ratio

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CHAPTER 1

INTRODUCTION

1.1 Background of study

It is now widely accepted that global climate change results in a rise within the frequency and intensity of climatic extremes, such as droughts and floods (Dore, 2005). More intense rainfall events had occurred all over the world and Malaysia has also received the impacts of the changes. In November 2019, the south region of Malaysia had an intense rainfall for almost a week that led to flash flood and was one of the worst tragedies that have ever happened, especially in Johor as the number of flood victims rise rapidly (Shah *et al.*, 2019). Prediction of rainfall events and climate changes in the future will lead to preparation before extreme events occur.

Climate prediction models and statistical analysis are a great tool to estimate future rainfall data. Various type of climate prediction models can be found to predict any climate data such as rainfall, temperature, wind velocity and others from different studies (Thorpe *et al.*, 2001; Claussen *et al.*, 2002; Hock & Holmgren, 2005; Gagnon *et al.*, 2005; Robinson & Catling, 2012; Bajracharya *et al.*, 2018). However, the General Circulation Model (GCM) has been used in many studies all over the world to predict future rainfall, temperature and other climate properties. GCMs is the infamously mathematically computer models that represent various global climate system of physical processes (Wilby, Dawson & Barrow, 2002).

GCM is a system of the many grid cells that represent horizontal and vertical areas on the Earth's surface which consider the potential level of greenhouse gases (GHGs). It computes water vapour and atmospheric cloud interactions, direct and indirect effects of aerosols on radiation and precipitation, changes in snow cover and sea ice, the storage of warmth in soils and oceans, surfaces fluxes of warmth and moisture, and large-scale transport of warmth and water by the atmosphere and oceans (Ghil & Robertson, 2000).

Canadian Earth System Model 2 (CanESM2) is one of the many center groups provide the GCMs data. Nevertheless, currently GCMs are depending on the Intergovermental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) which that is the modification from the AR4 series in terms of expected $\%CO_2$ and the climate variables. Proportionately, CanESM2 is an appropriate centre group to provide the GCMs data as CanESM2 represents a part of the modelling community's contribution to the IPCC Fifth Assessment Report (AR5) (Scinocca et al., 2008; IPCC, 2014b). IPCC AR5 made a finding of a new set of scenarios that provide time-dependent projections of atmospheric greenhouse gas (GHG) concentrations. The new scenarios are called Representative Concentration Pathways (RCPs) which consists four types of pathways; RCP 8.5, RCP 6, RCP 4.5 and RCP 2.6. Each number for each RCPs represents their forcing (Wayne, 2013). The RCPs are the latest iteration of the scenario process and it is important for climate change research to use RCPs data to investigate the plausible trajectories of different aspects of the future.

A statistical process is required to create a bridge between GCM scale and native scale because the GCM scale is just too vast. In this case, the downscaling method was chosen to minimize the GCM scale to the local scale. A process termed downscaling has been developed to formulate climate predictions at the local scale. Downscaling methods might be broadly classified into two categories, namely dynamical and statistical downscaling. Statistical is the most generally used compared to dynamical because it is often implemented easily in any region and cheap. In order to choose the suitable downscaling method, the desired spatial and temporal resolution of the climate information, resources and time constraints need to be considered (Wilby & Dawson, 2013).

Rainwater harvesting (RWH) system is known for capturing rainwater for local use. It has been implemented in all over countries in the world since years ago, and it has many different techniques and methods on implementing the system (Lo & Koralegedara, 2015; Alamdari *et al.*, 2018; Zhang *et al.*, 2019). RWH can also solve the water scarcity problem and decrease natural disaster phenomena. Water demand has been increasing worldwide at a rapid pace resulting in increasing demand caused by demographic changes, socioeconomic factors, changes in agricultural practices and climatic variation (Mohammed *et al.*, 2007). Hofman & Paalman (2014) concluded that rainwater harvesting could effectively reduced 13.9%, 30.2% and 57.7% of runoff volume in three cases of the maximum daily rainfall (207.2 mm), the average annual maximum daily rainfall (95.5 mm) and the critical rainfall of rainstorm (50 mm), respectively.

For most developing countries, RWH is listed together as the precise adaptation strategies that the water sector must undertake to deal with future global climate change, particularly in areas with high water demand. Some studies were administered to research the impact of global climate change on rainwater harvesting (RWH) supported by future rainfall variation (Fewkes, 2012; Kahinda *et al.*, 2010; Pina *et al.*, 2009; Helmreich & Horn, 2009).

1.2 Problem statement

Johor has been receiving increasing number of heavy rainfalls over the past years. According to the research made by Shafie (2009) a storm that blows from South East China Ocean and West Pacific Ocean cause heavy rainfall events that lead to major floods in December 2006 and January 2007. Kota Tinggi district was hit badly from the storms that brought 287 mm and 338 mm of rain in four (4) days recorded in Bandar Kota Tinggi for the year 2006 and 2007 respectively. There has been evidence made by the scientific community at NASA by Buis (2020) that as global temperatures increase, extreme precipitation will very likely increase as well but these researches have yet to have any significant effects on climate change in future rainfall intensities at a specific area of Johor.

Climate changes have affected rainfall intensities, especially in monsoon seasons which resulted in floods to occur without warning. Consequently, the rising temperature will lead to the unpredicted dry season. Besides, the rapid growth of population and expansion in urbanization may contribute to natural disasters. Besides, they have led to imposing growing demand and pressure on water resources (Che-Ani *et al.*, 2009). Rainwater harvesting is one of the ways to avoid water crisis as there will be increasing demand in future. Thus, it is important to estimate future changes in rainfall for finding suitable measures to mitigate this natural disaster problem but there has been little work exploring on the effect of climate change towards the amount of rainfall that could be harvested for a specific 100 m^2 of rooftop area in Johor.

1.3 Research objectives

The objectives of this study are;

1) To generate the long-term rainfall trend with respect to changes to the climate under three (3) different Representative Concentration Pathways Scenarios (RCPs).
2) To examine the changes in the trend of rainfall for interval year of Δ2030, Δ2050 and Δ2080.
3) To analyse the impact of climate change on the implementation of rainwater harvesting (RWH).

1.4 Scope of research

In order to achieve all the research objectives, the following tasks were carried out;

1. Collection of historical rainfall data (1988-2017) from the Department of Irrigation and Drainage (DID), Malaysia.

2. Projection of future rainfall for interval year of Δ2030, Δ2050 and Δ2080 using General Circulation Model with the climate variable data were retrieved from The Canadian Earth System Model 2 (CanESM2).
3. The climate modelling data were downscaled using Statistical Downscaling Model (SDSM).
4. Analyzing trend analysis for future rainfall data using the Mann-Kendall test.
5. Estimating amount of rainfall that could be harvested for a specific 100 m^2 of rooftop area for each selected station using Volume Harvested Formula.

The Canadian Earth System Model 2 (CanESM2) have 26 climate predictors. However, in this research validation of climate predictor selection for each stations was made and these are the climate modelling parameter used in this research; mean sea level pressure (ncepmslp), surface specific humidity (ncepshum), near surface relative humidity (nceprhum), mean temperature at 2m (nceptemp), relative humidity at 500hPa (ncepr500), relative humidity at 850hPa (ncepr850), 500hPa geopotential height (ncepp500) and 850hPa geopotential height (ncepp850).

There are three (3) major limitations in this study that could be addressed in future research. Firstly, eight (8) rainfall stations across Johor were chosen based on the data received from DID, Malaysia. The selected station represents each district in Johor that had less than 10% missing data (<10). Unfortunately, none of Mersing district rainfall stations can be used due to the insufficient daily rainfall data. Secondly, the geographical element was not considered in choosing the rainfall stations. Most of the stations had more than 10% missing data (>10%) which led to difficulty in finding the most appropriate method to be used. Boughton (2007) stated that any rainfall data can be discarded if the catchments in which there were so many periods of missing data that the period available for calibration and validation for projection was too short. Thirdly, even though rainfall is associated well with temperature, however, temperature was not considered in the current study.

1.5 Research Significance

In this subchapter, the importance of the study and the potential end-results are deliberated generally as below:

- As was mentioned in Section 1.1, climate change has affected rainfall distribution across the world, including Malaysia. The latest flood event in early December 2019 that affected Johor proved that climate change gave impact to the rainfall variability, even though Johor did expect to receive the North-east monsoon where rain falls more than the usual month. However, the intensity of the rainfall was higher compared to the past years. Hence, the climate model needs to be implemented as there has been limited research on the prediction of rainfall events, specifically in Johor using the General Circulation Models (GCMs). This would help in projecting future rainfall for the next 90 years.
- A climate model is often too broad and difficult to understand. This study will explain the variety of the models but will highlight more on GCMs as the aim of this research will be using GCMs as the climate prediction model.
- Rainfall trend analysis assists in the identifications of possible trends in climatic parameters, including the wet and dry periods. No comprehensive research has been conducted on finding the trend for future rainfall events in Johor. Hence, a possible trend within the projected future rainfall are going to be determined.
- The estimation of harvested rainwater volume using future rainfall data in Johor could provide some information that can be used for future planning.

1.6 Outline of the Thesis

Chapter 1 explains the goals, the scopes of the study and therefore, the importance of the research. This chapter also provides an overall picture of the work activities carried out within the thesis.

Chapter 2 provides a thorough review of research associated with the global climate change impacts rainfall variability, climate modelling, a statistical tool to downscale climate data and rainwater harvesting implementation using projected rainfall data. A review paper on climate change effects on rainfall has been published in the International Journal of Integrated Engineering.

Chapter 3 provides the outline of the methods used, the study area, the rainfall data used and the climate predictors were chosen. The procedures of finding missing data of daily rainfall are also given. This chapter also presents preliminary analytical results on the assessment of climate predictors data that were downscaled to local scale using SDSM. The procedure of retrieving the climate predictors, screening of predictors, and calibration and validation processes to find the most appropriate climate predictors for each selected rainfall stations are also discussed.

Chapter 4 consists of main findings in this research which are the prediction of future rainfall in Johor, the future trend analysis and the results of the potential volume of rainwater that would be collected in the future. This chapter reveals the procedure of predicting rainfall using GCM which were downscaled using SDSM for three (3) different climate scenarios of GCMs predictors of Hadley Center General Circulation Model (CanESM2); RCP 2.6, RCP 4.5 and RCP 8.5. Besides, the future annual rainfall trend results are also presented. The developed equation of harvested rainwater volume is presented in this chapter and also the differences between past and future harvested rainwater were discussed.

Finally, Chapter 5 provides a summary and hence the principal inference is drawn from individual components of the analysis. Recommendations are also presented for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reviews the impacts of climate change towards rainfall, the use of climate modelling to project future rainfall, supporting statistical tool to help lessen the scale of climate modelling data and RWH implementation. The changes to the climate is difficult to predict because of rapid growth of population, urbanization, industrialization, and irrigated agriculture that increases pressure on existing water resources and wish to be acknowledged by humankind (Lee *et al.*, 2016). Climate change will cause a general intensification of the earth's hydrological cycle within the next 100 years with generally increased in precipitation, evatransporation, the occurrence of storms and significant changes in biogeochemical processes influencing water quality (Pandey *et al.*, 2003). In Malaysia, the awareness of climate change is still shallow. The public knew what the causes and effects of climate change are but tend to ignore the aftermath that could happen towards the earth.

Sea level rise is one of the significant impacts of climate change due to the global warming that causes ice from the south and north Antarctica to melt. Rainfall intensity was also affected by the changes in climate (Ahmad Tarmizi *et al.*, 2019). Rainfall varied from year to year and over decades and resulted in changes in the

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